A discrete element approach for modelling the compression of crop stems

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Abstract

The discrete element method (DEM) offers a powerful tool for simulating the interactions of large numbers of particles. Recently, DEM was used to simulate the interactions of tubular particles. While the existing linear elastic and Hertzian contact models can approximate the reversible compression for small deformations, they are inadequate for larger deformations. Here, the force-deformation behaviour is highly non-linear and plastic. In this study, data based contact models were developed for crop stems. These models combine realistic deformation behaviour with a minimal number of model parameters. Furthermore, the effect of plastic deformation and damage was incorporated in the model. The contact models were successfully used to validate, through comparison of simulations and measurements, individual stem and bulk compression. A good agreement was found between both. These validated DEM contact models for compression of crop stems allow to simulate the processing of large numbers of crop stems.

Keywords: DEM, Simulation, Compression, Contact model, Crop stem,

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1. Introduction

The importance of simulations for the optimization of various processes is increasing because simulations can provide a huge potential in terms of process understanding and development of machines. Development costs can be reduced by evaluating machine adjustments in early stages via computer simulations before building costly and complex prototypes. This simulation approach also enables the investigation of new and unconventional ideas with acceptable effort (Jünemann et al., 2013). To obtain realistic simulations, both the machine and the material to be processed should be simulated with sufficient accuracy. In the case of biomaterial processing, the biological variation adds an extra challenge.

In this study, we focus on the processing of crop stems by harvesting machines such as combines and balers. When the interactions between individual stems or between stems and machine components are important, traditional bulk approaches (e.g. finite element modelling) are often inadequate. As these interactions take place at the particle level, a modelling framework on this level is required.

1.1. Discrete element modelling of crop stems

When modelling the behaviour of a collection of particles, Discrete Element Modeling (DEM) is a logical choice as it allows to describe the behaviour of each particle through its interactions with the other particles and the system elements (Tijssens et al., 2003). In this way, the influence of

23 particle properties (both geometrical and mechanical properties) and bound-
 24 ary conditions (shape and motion of machine parts) can be assessed with
 25 a set of in silico experiments that can be run in parallel (Lenaerts et al.,
 26 2014). To obtain reliable simulation results, the virtual stems must have re-
 27 alistic geometries and deform realistically during contact. The stems should,
 28 therefore be compressible in both longitudinal and radial direction and also
 29 bendable in every direction. However, few reports have been published on
 30 particles with large aspect-ratio, as simulating the movement and collisions of
 31 these particles is considerably more complex than for rigid spherical particles.

32
 33 In the last years, tubular particles were created by a number of researchers
 34 (Ross & Klingenberg, 1997; Favier et al., 1999; Grof et al., 2007; Kattenstroth
 35 et al., 2011; Geng et al., 2011; Guo et al., 2012b, 2013a,b; Nguyen et al., 2013;
 36 Grof & Štěpánek, 2013; Jünemann et al., 2013; Kajtar & Loebe, 2014; Nan
 37 et al., 2014; Lenaerts et al., 2014; Leblicq et al., 2014, 2015a). The accuracy
 38 of the simulations with these particles varies greatly. Ross & Klingenberg
 39 (1997) studied the dynamics of flowing suspensions of rigid and flexible fibres
 40 composed of linked rigid bodies. They demonstrated that the method can
 41 reproduce known dynamical behaviour of both types of fibres in a flow field.
 42 Favier et al. (1999) developed a method for representing smooth-surfaced,
 43 axi-symmetrical particles using overlapping spheres of arbitrary size. Vir-
 44 tual straw stems were developed by Kattenstroth et al. (2011) by connecting
 45 spheres. The stems in this research were, however, rigid and unbendable.
 46 The same method was used to create rigid fibres and rodlike particles (Grof
 47 et al., 2007; Grof & Štěpánek, 2013; Nan et al., 2014). Flexible filamen-

48 tous particles composed of chains of rigid bodies connected through ball and
 49 socket joints were developed by Geng et al. (2011); Guo et al. (2013a,b); Grof
 50 & Štěpánek (2013). Jünemann et al. (2013) and Kajtar & Loebe (2014) cre-
 51 ated bendable crop stems by connecting spheres with cylindrical bonds. Guo
 52 et al. (2012b) compared glued-spheres particles and true cylindrical particles
 53 and concluded that for smooth particles the most realistic results are ob-
 54 tained with cylindrical particles. Guo et al. (2012a) also described methods
 55 for more optimal contact detection and dense packing of cylindrical particles.
 56 Lenaerts et al. (2014) created segmented bendable straw stems by connecting
 57 rigid cylinders with flexible configurable bonds. They used the DEMeter++
 58 software (Tijssens et al., 2003) to simulate grain-straw separation and vali-
 59 dated the results with measurements. Leblicq et al. (2014, 2015a) improved
 60 the bending model of Lenaerts et al. (2014) and obtained tubular particles
 61 (crop stems as well as metal and plastic tubes) with realistic bending and
 62 buckling behaviour.

63 *1.2. Contact models for tubular particles in DEM*

64 The discrete element method uses the Newton-Euler equations of motion
 65 to compute the translatory and rotational movements of every particle in the
 66 simulation. Due to these movements, particles make contact and interact.
 67 Interacting particles are allowed to virtually overlap. The normal forces
 68 which particles exert on each other are determined by a contact model (based
 69 on this virtual overlap and potentially on the contact history). Contact
 70 models for calculating normal and tangential forces are usually analogues
 71 models based on spring, damper and friction elements (Jünemann et al.,
 72 2013).

73 Contact forces are typically decomposed into a normal and tangential
74 component, with respect to the contact surface. The normal component of
75 the contact force acting on a particle is generally described as a function
76 of the virtual overlap (δ) and its time derivative ($\dot{\delta}$) (Tijskens et al., 2003).
77 The simplest model assumes a linear elastic component and a linear viscous
78 damping.

$$F_n(\delta, \dot{\delta}) = k_1\delta + \gamma_1\dot{\delta} \quad (1)$$

79 For viscoelastic materials, a non-linear model, based on Hertz contact law
80 can be derived (Tijskens et al., 2003):

$$F_n(\delta, \dot{\delta}) = k_2\delta^{3/2} + \gamma_2\delta^{1/2}\dot{\delta} \quad (2)$$

81 Tangential contact forces arise when two particles take part in an oblique
82 collision or when contacting particles are rotating relative to each other.
83 The simplest contact model in the tangential direction describes Coulomb
84 friction with a viscous damper enforcing the no-slip regime. As for impact in
85 the normal direction, realistically behaving contact models in the tangential
86 direction also require elastic and viscous terms (Tijskens et al., 2003).

87 These basic contact models were also used to model the interactions be-
88 tween tubular particles. Grof et al. (2007), Nguyen et al. (2013), Jünemann
89 et al. (2013), Kajtar & Loebe (2014) and Leblicq et al. (2015a) used linear
90 spring-damper systems. Guo et al. (2012b), Nan et al. (2014) and Lenaerts
91 et al. (2014) used Hertz contact models. All studies used Coulomb friction.

92 1.3. *Limitations of the existing contact models*

93 Although it has been shown that stem deformation processes are defi-
94 nitely non-linear (Leblicq et al., 2015b), in DEM the processes have typically
95 been assumed to be linear. Only for the first, linear elastic part of the force-
96 deformation curve this assumption is acceptable. At larger deformations,
97 ovalisation, buckling and cracking of the particles takes place. This results
98 in a highly non-linear and plastic deformation behaviour. Plastic deforma-
99 tion implies that stems will respond differently to re-compression or further
100 deformation, which is ignored by the DEM contact models. The bulk be-
101 haviour of a collection of stems is the sum of the behaviours of the individual
102 stems. Incorrect stem behaviour could thus result in incorrect simulation
103 results and incorrect decisions for machine optimisation. Therefore there is a
104 need for DEM contact models that can realistically describe the deformation
105 behaviour of crop stems and that takes plastic deformation into account.

106 1.4. *Objectives of this study*

107 To the knowledge of the authors, no studies have been conducted to define
108 DEM contact models for tubular particles describing the contact behaviour
109 realistically both for undeformed and damaged stems. Therefore, the general
110 objective of this study was to create and validate these contact models. In
111 order to achieve this goal, there are some specific objectives. First, the forces
112 required to deform crop stems need to be measured. Then, the deformation
113 of individual stems has to be modelled using data based models. Afterwards,
114 the interactions between individual stems and between stems and plates (rep-
115 resenting a machine part) need to be modelled. Finally, the contact models
116 need to be validated both on stem and bulk level.

Fig. 1. Bendable straw in DEMeter++ (Lenaerts et al., 2014)

117 2. Material and methods

118 In this study, we started from the segmented crop stems developed by
 119 Lenaerts et al. (2014) in DEMeter++ (Fig. 1). Each segment consists of a
 120 capsule connected to its adjacent capsules by joints. The joints are respon-
 121 sible for the flexibility of the particle. In each joint, a number of spring-
 122 dampers (k_b , c_b) is placed which creates a moment that counteracts bending
 123 forces. The tensile stiffness of each segment of the straw particle is provided
 124 by one spring and damper (k_t , c_t) per segment. The Werner and Haff model is
 125 used to model the tangential contact forces (friction) (Haff & Werner, 1986).
 126 When stems interact, they virtually overlap and exert normal forces on each
 127 other. An extra spring-damper system (k_c , c_c) is responsible for these forces.
 128 However, in this study the value of the contact spring is not a constant (as
 129 is the case in the linear elastic and in the Hertz model), but depends on the
 130 overlap (δ) and the previous deformations (d) of the particle ($k_c = f(\delta, d)$).
 131 The normal force is then:

$$F_n(d, \delta, \dot{\delta}) = F_{n, \text{spring}} + F_{n, \text{damper}} = k_c \delta - c_c \dot{\delta} \quad (3)$$

132 The dampers prevent the elements from oscillating, dissipate energy and
133 stabilize the simulation.

134 *2.1. Measurements of the mechanical properties of stems*

135 The values for the normal spring force were determined experimentally.
136 The deformations imposed during the measurements were chosen as such
137 that the range of deformations covers the deformations during processing.
138 Two types of interactions occur: stem-stem interactions and stem-machine
139 interactions. These interactions were measured with the set-ups shown in
140 Fig. 2. Both types of measurements were conducted with a single column
141 testing machine (Type LS1 Material Tester, LLOYD materials testing, West
142 Sussex, UK) at a speed of 1 mm/s. In Fig. 2(a) the set-up for measuring
143 the interaction between a stem and a plate is displayed. When the top plate
144 moves down the stem is compressed and the required force is recorded with
145 a 50 N loadcell (Type LS Loadcell 50N, LLOYD Instruments, West Sussex,
146 UK). In Fig. 2(b) the set-up for measuring the compression of a stem due to
147 the interaction with a stem-shaped object is shown. The stem is placed on
148 a metal bar that has a diameter corresponding to that of an average wheat
149 stem (3.5 mm, Leblicq et al. (2015b)). The plunger has the same dimensions.
150 The stem is thus compressed between two metal stems.

151

152 To determine the effect of plastic deformation and damage, the measure-
153 ments are not performed in one run, but step-wise. In every cycle the plunger
154 (either plate or metal stem) moves down an additional 0.1 mm relative to
155 the previous cycle and then returns to the initial position. The deformation
156 is thus incrementally increased (Fig. 3 (black)).

(a)

(b)

Fig. 2. Set-up for measuring stem compression
(a) stem-plate interaction, (b) stem-stem interaction

Fig. 3. black: plunger movement, red: maximum historical deformation (MHD)

157 To identify the variability of the deformation behaviour thirty measure-
 158 ments were performed on wheat stalks for each set-up. The stalks were
 159 randomly harvested by hand from one field in northern France in August
 160 2014. Prior to the measurements the stems were cut to a length of 5 cm. All
 161 internodes were used.

162 2.2. From measured data to contact model

163 The measured force-deformation data can be used to determine the con-
 164 tact forces ($F_{n,spring}$ in Eq. (3)) of interacting particles. For this, the data are
 165 first processed and look up tables (LUT's) are made from the data (section
 166 2.2.2). These LUT's are used to develop contact models. First, the interac-
 167 tions between stems and rigid structures are modelled. Due to the rigidity of
 168 the structure only the stems will deform. Afterwards the interaction between
 169 different stems is modelled. Here both stems will be (plastically) deformed.
 170 The extend to which each stem deforms is dependent on the relative stiffness.

171 2.2.1. *Data processing*

172 During processing, the data points with negative indentation are removed
173 (the plunger is not making contact with the stem). The data is divided into
174 two groups. The data where the plunger is moving down and the stems get
175 deformed and the data where the plunger is retracting. For each measured
176 data point the maximum historical deformation (MHD) is determined (Fig. 3
177 (red)). During the first cycle, while the plunger is moving down, the MHD is
178 increasing. When the plunger retracts, the MHD stays constant and is equal
179 to the maximum deformation of the first cycle. During the second cycle, the
180 MHD will only increase after the plunger has exceeded the deformation of the
181 first cycle. The MHD is thus always equal to or larger than the indentation.
182 Each data point consist thus of three values: indentation, force and MHD.
183 Each pair of values for the MHD and the indentation corresponds to a value
184 of the force. This relation is used to make LUT's from the data.

185 2.2.2. *Look up tables*

186 An equidistant grid was formed by the vectors of the MHD and the in-
187 dentation. Linear interpolation was then used to determine the value of the
188 force for each grid point. The normal force can, therefore, also be determined
189 for intermediate values of the MHD and the indentation that were not mea-
190 sured. For all thirty stem-stem measurements and for all thirty stem-plate
191 measurements, look up tables were built.

192 2.2.3. *Determination of deformation forces from the LUT's*

193 When stems in DEM interact, they overlap. This virtual overlap corre-
194 sponds to the measured indentation. Each segment of the virtual stems has

195 a memory, in which the maximum historical overlap/deformation (MHD) is
 196 stored. In every time step of the simulation and for each segment the overlap
 197 with neighbouring segments is calculated. From this overlap and from the
 198 stored MHD, the corresponding force can be obtained from the look up table
 199 for that stem.

200 *2.2.4. Switching between look up tables*

201 Depending on whether the deformation increases or decreases a different
 202 LUT is used (e.g. the LUT in Fig. 9(a) can be used for increasing indenta-
 203 tion and the LUT in Fig. 9(b) for decreasing indentation). Only taking the
 204 previous time step into account to determine whether the deformation is in-
 205 creasing or decreasing is insufficient. High frequency vibrations would cause
 206 a constant switching between LUT's. Therefore, not only the indentation
 207 from the previous time step, but also a weighted change in indentation ($d\delta$)
 208 is stored per contact. This weighted change of indentation is calculated as
 209 suggested by Janert (2013):

$$d\delta_t = \frac{d\delta_{t-1} + \left(\frac{\delta_t - \delta_{t-1}}{\alpha}\right)}{1 + \frac{1}{\alpha}} \quad (4)$$

210 The weighted change of indentation ($d\delta_t$) is a function of the previously cal-
 211 culated weighted change of indentation ($d\delta_{t-1}$) and the difference between
 212 the overlap in the current and the previous time step ($\delta_t - \delta_{t-1}$). The param-
 213 eter α determines the weight of the current time step in the calculation of
 214 $d\delta_t$. A higher value of α makes $d\delta_t$ less sensitive to vibrations. When $d\delta_t$ is
 215 positive the indentation is increasing. When $d\delta_t$ is negative the indentation
 216 is decreasing. The value of $d\delta_t$ determines thus which LUT has to be used.

217 2.2.5. *Contact mechanics*

218 Using LUT's, we now have virtual stems that behave realistically when
 219 compressed. This does, however, not mean that the stems interact realisti-
 220 cally. The contact force is indeed not the sum of the compression forces of
 221 both particles separately, nor is it the average of both. Also, the deformation
 222 cannot evenly be distributed over both particles. Particles with less deforma-
 223 tion resistance (e.g. stems with smaller wall thickness or stems which have
 224 already been deformed) will deform more and sustain more plastic deforma-
 225 tion. This again makes it more likely that they will be damaged more during
 226 future interactions. This process will continue until a stem is completely
 227 crushed and the stem walls make contact. The resistance to deformation
 228 is then strongly increased. The extent to which each stem is deformed and
 229 damaged thus depends on the relative resistance to deformation.

230

231 The virtual overlap in DEM corresponds to physical deformation. In
 232 reality, however, stems are not evenly deformed. In this way, also the overlap
 233 can not be evenly distributed over the two virtual stems. The stem with the
 234 least resistance to deformation is attributed the largest part of the overlap
 235 ($a\delta$), where a is the percentage of the overlap for that stem. The second stem
 236 will contain the remaining part of the overlap. This part is equal to $(1 - a)\delta$.
 237 The sum of the overlap of the two stems is, as a result, equal to the total
 238 overlap.

$$a\delta + (1 - a)\delta = \delta \quad (5)$$

239 The forces between two stems (determined by the stored MHD of each stem

240 and the part of the overlap that each particle receives) should however, ac-
 241 cording to Newton’s third law, always be equal in magnitude (but opposite
 242 in direction). Each time particles interact, this distribution of the overlap
 243 has to be determined.

244 The determination of the distribution of the overlap corresponds to find-
 245 ing a value for a such that the forces of the two stems (F_1 and F_2) are equal.

$$F_{N1} = F_{N2} \quad (6)$$

246 The forces F_{N1} and F_{N2} of both stems are a function of the mechanical
 247 properties (the LUT’s), the MHD’s (MHD_1 and MHD_2), and the virtual
 248 overlaps ($a\delta$ and $(1 - a)\delta$).

$$F_{N1} = LUT_1(MHD_1, a\delta) \quad F_{N2} = LUT_2(MHD_2, (1 - a)\delta) \quad (7)$$

249 The bisection method is used to solve Eq. (6) and thus to determine the value
 250 of a , F_{N1} and F_{N2} . Afterwards, it is determined whether the current overlap
 251 of each particle is larger than the MHD of that particle. If this is the case,
 252 the MHD is updated.

253 2.3. DEM parameters

254 Apart from the contact model parameters, all parameters of the bendable
 255 stems have been defined similar to those in Lenaerts et al. (2014). The
 256 parameter values are listed in Table 1.

257 2.4. Stem simulations

258 To validate the contact models, stem simulations corresponding to the
 259 stem measurements from section 2.1, were conducted. The virtual stems

Table 1. DEM parameters

Parameter	Value	Unit	Meaning
k_b	0.75	N/m	spring for bending
c_b	$2.5e^{-4}$	kg/s	damper for bending
k_t	100	N/m	spring for tension
c_t	0.1	kg/s	damper for tension
c_c	0.1	kg/s	damper for compression
μ	0.3	-	friction coefficient
c_μ	10	kg/s	damper for friction

Fig. 4. Stem simulations

(a) Simulation of stem-plate interaction (equivalent to Fig. 2(a)), (b) Simulation of stem-stem interaction (equivalent to Fig. 2(b))

260 were given diameters equal to those from the measured stems (Table 2). The
 261 stems were compressed by a virtual metal plunger (both the plate and the
 262 metal stem, Fig. 4). The plunger was given a LUT for steel. This LUT
 263 was built from the stress-strain curve of steel (Rasmussen, 2003). The forces
 264 that are required for an equal amount of deformation are 40 times higher for
 265 steel than for wheat straw (Mohsenin, 1986). This will result in an almost
 266 complete deformation of the stem and almost no deformation of the plunger.

267 The overlap is thus nearly entirely for the stem. In these simulations, the
268 compression was also performed stepwise as was done in the experiments.

269 *2.5. Bulk simulations*

270 To validate the contact model on a bulk level, the compression of fifty
271 stems to 50 N was simulated. Each virtual stem consisted of five segments and
272 had a total length of 5 cm. Each stem was given two pairs of LUT's. One pair
273 for the stem-stem interaction (both increasing and decreasing indentation)
274 and one pair for the stem-plate interaction. The LUT's were randomly chosen
275 from the thirty LUT's that were created from the stem measurements. The
276 stems were placed parallel to each other on the bottom of a compression
277 box (6 cm wide, 6 cm long and 10 cm high). Before compression, the box
278 was shaken two times with an amplitude of 10 cm and a frequency of 4 s^{-1}
279 to randomise the orientation of the stems (Fig. 5(a)). This initialisation
280 method was chosen because it could both be simulated and reproduced in
281 validation experiments. After the randomisation, the stems were compressed
282 at a speed of 1 mm/s and the force on the plunger was recorded (Fig. 5(b)).
283 This simulation cycle (random assignment of stem properties, initialisation
284 and compression) was repeated twenty times.

285 *2.6. Bulk measurements*

286 To validate the bulk simulations, twenty bulk measurements were con-
287 ducted. The same conditions were applied. The compression box had the
288 same dimensions. The fifty stems were first placed parallel in the box and
289 then shaken for initialisation (Fig. 6(a)). After randomisation, the stems
290 were compressed at a rate of 1 mm/s (Fig. 6(b)). The stems were obtained

Fig. 5. Bulk simulations

(a) stem orientations after initialisation (equivalent to Fig. 6(a)), (b) bulk compression (equivalent to Fig. 6(b))

from the same field as the stems from the stem measurements. Prior to the measurements, the stems were cut to a length of 5 cm. All internodes were used.

2.7. Modelling bulk compression

Due to the randomization of the stem orientations during initialization, a one on one comparison of the simulation and the measurement results was not possible. To compare the results, an existing compression model was fitted to the stress-strain data. The following exponential model was used (O'Dogherty, 1989):

$$\sigma = me^{n\epsilon} \quad (8)$$

Fig. 6. Bulk measurements
(a) stem orientations after initialisation, (b) bulk compression

where σ is the stress, ϵ is the engineering strain and m and n are empirical crop parameters. The model was fitted separately to the loading and unloading part of the simulated and measured compression profiles.

The validation consists of determining whether the compression model can describe both the simulated and measured compression profiles. When the model parameters for the simulations and the measurements are not significantly different, this indicates that the bulk deformation behaviour of crop stems can be estimated based solely on the stem properties.

3. Results and discussion

3.1. Stem measurements

Stem measurements were used to create virtual stems with realistic geometries and realistic contact behaviour. Typical force-deformation measurements for stem-plate and stem-stem compression are displayed in Fig. 7. The deformation behaviour is in both cases highly non-linear and plastic.

Thirty wheat stems were measured for both types of compression. Table 2 gives a summary of the stem diameters used in each set-up. These measured stem diameters were also given to the virtual crop stems.

Table 2. Stem diameters (for both compression types thirty wheat stems were measured)

Compression type	Average stem diameter	Standard deviation on the stem diameters
stem-stem	4.05 mm	0.60 mm
stem-plate	3.98 mm	0.59 mm

An example of a typical measured stepwise deformation profile of a wheat

Fig. 7. Measured compression profiles of wheat stems. The hysteresis is a result of the plastic deformation.

(a) stem-plate interaction, (b) stem-stem interaction.

black: measured data, red: linear elastic model, blue: Hertz model

The interaction of a cylinder with a surface (a) results in a line contact. In this situation, the Hertz model predicts a linear contact force.

Fig. 8. Stepwise stem-stem deformation (experimental results)

For clarity loading is displayed in blue and unloading is displayed in red

stem is displayed in Fig. 8. This stepwise stem-stem measurement shows how the deformation behaviour changes due to plastic deformation. It also shows the reaction to the retraction of the plunger and gives information about hysteresis.

3.2. Graphical representation of the look up tables

The stepwise deformation data were used to create look up tables. A graphical representation of the Look up tables (both increasing and decreasing indentation) built from the data in Fig. 8 is shown in Fig. 9. Each horizontal line represents one cycle in the stepwise deformation. Because the MHD is always larger than the indentation/overlap, there are no data in the lower right corner. For all measurements (both stem-plate and stem-stem) look up tables were built.

Fig. 9. Look up tables for the stepwise stem-stem interaction of Fig. 8. A grid size of 0.01 mm was used. The diameter of the stem was 3.6 mm. The maximum deformation/overlap in these LUT's (3 mm) thus corresponds to a strain of 0.833.

(a) Downward movement of the plunger (increasing deformation), (b) Upward movement of the plunger (decreasing deformation)

Fig. 10. Distribution of the overlap of the two interacting stems and resultant forces (Eq. (7))

(a) black: resulting contact force, blue: force-deformation profile of the first stem, red: force-deformation profile of the second stem (b) black: total overlap, blue: overlap of the first stem, red: overlap of the second stem,

3.3. Contact forces

In Fig. 10(a) the force-deformation curves of two stems with equal diameter (red and blue) are displayed. The contact force (the force which both particles exert on each other during interaction) is displayed in black. In accordance with Hertzian theory, the contact force is smaller than the force required to deform each stem separately. The contact force corresponds most with the deformation force of the easiest deforming stem (red). If a particle does not (or very little) deform, the contact force will be equal to the deformation force of the other particle. In Fig. 10(b) the distribution of the overlap is displayed. The stem that deforms most easily (red) has the largest overlap. The sum of both overlaps (red and blue) is equal to the total overlap (black).

343 3.4. Stem simulations

344 To validate the contact model stepwise compression measurements were
345 conducted on wheat stems. These measurements were repeated in simulation.
346 In Fig. 11(a) a typical stem-plate measurement (black) and the corresponding
347 simulation (blue) are displayed. To demonstrate that the LUT's can generate
348 forces corresponding to MHD's and indentations that were not measured, a
349 different step size was used in the simulations and in the measurements. A
350 typical stem-stem measurement (black) and the corresponding simulation
351 (blue) are displayed in Fig. 11(b). It is clear that the simulations correspond
352 well with the measurements. This was expected since the stem deformation
353 model is data based. A similar result was obtained for all thirty stem-stem
354 measurements and for all thirty stem-plate measurements.

355 In an analytical model, the same degree of accuracy would require many
356 parameters to be estimated. A data based model is more accurate and less
357 computationally expensive. However, it is less generic. Stem Properties for
358 new conditions must be measured since they cannot be calculated from the
359 model.

360 3.5. Bulk compression

361 To validate the contact model, bulk compression measurements were con-
362 ducted on randomly orientated stems (Fig. 12(a)). These measurements were
363 also simulated with the data based contact model (Fig. 12(b)). For clarity,
364 only one measured stress-strain profile and the best corresponding simulation
365 profile are displayed in Fig. 12(c). For both compression profiles the bulk
366 model (Eq. (8)) is plotted (both for loading and unloading).

Fig. 11. Stem compression (black: measurement, blue: simulation (loading), red: simulation (unloading))
(a) stem-plate compression, (b) stem-stem compression

367 The values of the model parameters, obtained by fitting Eq. (8) to all
368 stress-strain profiles, are summarized in Table 3. From the large standard
369 deviations (σ) of the model parameters (both for m and n and both for
370 loading and unloading), it becomes clear that large variations exist in the
371 measured force-deformation behaviour, even for stems from the same field.
372 This is partly due to different stem characteristics, but also due to different
373 stem orientations after initialization. The same phenomena can be observed
374 in the simulations. The R^2 -values are high both for the measured and the
375 simulated compression profiles indicating that both can be described using
376 the existing compression model.

377 The values of the fitted parameter m (used to describe the bulk compres-
378 sion) are not significantly different for the measurements and simulations
379 (p-values from the t-tests: 0.194 (loading) and 0.415 (unloading)). The p-
380 values indicate that the t-test does not reject the null hypothesis (the dif-

Fig. 12. Bulk compression (black: measurements, blue: simulations with LUT's)
(a) all measured bulk profiles, (b) all simulated bulk profiles, (c) one measured and one simulated profile and the corresponding bulk models (red)

Table 3. Estimated bulk crop parameters for both the simulations and the measurements (N: amount of samples, m and n: model parameters (Eq. (8)), μ : mean, σ : standard deviation)

	N	m		n		R^2	
		μ	σ	μ	σ	μ	σ
Measurement							
Loading	20	4.156	2.150	5.182	2.572	0.995	0.006
Unloading	20	0.148	0.108	22.452	2.365	0.996	0.005
Simulation (data based contact model)							
Loading	20	3.532	2.313	4.663	1.983	0.995	0.005
Unloading	20	0.229	0.136	22.581	2.956	0.989	0.008

381 ferences between the values of $m_{measurements}$ and the values of $m_{simulations}$
 382 have a mean equal to zero) at the 5% significance level. The same is true for
 383 parameter n (p-values for the comparison of measurements and simulations:
 384 0.284 (loading) and 0.804 (unloading)). If the differences are not significant,
 385 no distinction can be made between the measurements and the simulations.
 386 Therefore, the bulk deformation behaviour of crops can be determined based
 387 on the properties of individual stems using databased contact models and
 388 DEM simulations.

389 It should also be noted that, for the simulation of the processing of crops
 390 in agricultural machinery not only realistic compression models but also re-
 391 alistic bending and friction models are required. Stems which exhibit differ-
 392 ent compression behaviour will indeed also bend differently. The biological
 393 variability should therefore also be taken into account. In addition, Leblicq
 394 et al. (2015b) showed that the bending behaviour of crop stems is highly non-
 395 linear and plastic. A data-based approach could also offer a solution to this

396 problem. Also the influence of friction (both between individual stems and
397 between stems and machine components) should be studied in more detail.

398 4. Conclusions

399 Linear elastic and Hertzian contact models can approximate interaction
400 forces between tubular particles for small deformations. However, as har-
401 vesting machines cause larger deformations, realistic simulations can only be
402 obtained if the behaviour for larger deformations is also realistic. Therefore,
403 contact models need to realistically describe interactions over the entire de-
404 formation range. To meet this need, in this study data based contact models
405 were developed for crop stems. For this purpose, look up tables were created
406 from stem measurements. These measurements were performed stepwise to
407 assess the influence of plastic deformation. To determine the contact forces
408 between stems, the virtual overlap was divided over both interacting particles
409 such that the individual deformation forces are equally large. The interaction
410 between individual stems and between stems and plates was simulated and
411 validated with measurements on both stem and bulk level. A good correla-
412 tion was found between both.

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417 6. References

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